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The role of bioenergy in low-carbon energy transition scenarios: A case study for Quebec (Canada)

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ABSTRACT

The Canadian province of Quebec has set for 2030 a greenhouse gas (GHG) emission reduction target of 37.5% below 1990 levels. Meeting such a reduction target requires in particular a rapid transition to a low-carbon energy system. This paper proposes prospective energy scenarios for Quebec up to 2030, under different GHG emission reduction constraints (up to a 40% reduction). The main objective is to explore the role of bioenergy in achieving the reduction targets. Our analysis is based on the North American TIMES Energy Model (NATEM). It belongs to the MARKAL/TIMES family of models supported by the International Energy Agency, and includes a detailed bioenergy sector. Compared to the reference case (baseline), our results indicate a larger share of bioenergy in 2030 (up to a threefold increase in the most stringent GHG reduction scenario), with up to a fourfold increase in the total amount of feedstock used for bioenergy production. Our study envisions thus a much larger penetration of bioenergy than the one proposed by the government of Quebec in its 2030 Energy Policy.

1. Introduction

Canada ratified the Paris Agreement on October 2016 at the 21st Conference of the Parties [1], where virtually all of the world's nations (195 countries) agreed to reinforce the response to mitigate climate change under a common framework, "[…] *including by holding the increase in global average temperature well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*" [2]. More concretely, Canada communicated its economy-wide greenhouse gas (GHG) emission reduction target of 30% below 2005 levels in 2030, including the use of international emission credits, and the contribution of the land use, land use change and forestry (LULUCF) sector. Excluding the latter, this translates into a GHG emission reduction target of 20% below 2005 levels and 3% below 1990 levels, a commitment that could be inadequate according to some observers [3].

The effects of climate change have already begun to manifest in many ways in Quebec. Moreover, the acceleration of climate change in the coming years will accentuate these impacts and increase the risks to populations. Therefore, the province intends to contribute actively to international efforts to reduce GHG emissions by setting its own target for 2030: a 37.5% reduction below 1990 levels [4]. This commitment represents the most ambitious among the 13 provinces and territories in Canada.

Meanwhile, several initiatives were undertaken across the country to study transition scenarios toward a low-carbon energy system, including the analysis of more ambitious GHG reduction targets for 2050 which are more compatible with a well below 2 °C target. For instance, the Trottier Energy Futures Project proposes possible pathways to a deeply decarbonized Canadian economy using an optimization energy model [5,6]. The study shows that three fundamental transformations need to simultaneously occur in order to achieve ambitious reduction targets in Canada: i) electrification of end-uses (more than half of final energy consumption), ii) decarbonization of electricity generating supply, and iii) energy efficiency measures to decrease final consumption. Although electrification seems a relatively clear mitigation strategy for several end-use sectors, other sectors present a more ambiguous situation due to the uncertainty of technological advances which may affect them. Depending on future technological developments, bioenergy could represent a significant portion of the future primary and final energy demand for specific end-uses such as heavy freight transportation.

The International Energy Agency forecasts an important deployment of cellulosic ethanol and biomass-to-liquids diesel in 2050, as

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global biofuels could provide 27% of total transport fuels [7]. The European Commission Roadmap for moving to a low carbon economy in 2050 also points to the necessity of developing second and third-generation biofuels to mitigate climate change while addressing other sustainability issues associated with biofuels in general such as land use change, water management and biodiversity [8]. However, advanced biofuels are more expensive, which may lead to high mitigation costs for the society [9]. Several factors might affect the potential market penetration of bioenergy solutions such as availability of biomass feedstock, fossil fuel prices or future climate and energy regulations [10]. There is therefore a need for studies that do not focus on a particular bioenergy application but adopt a holistic approach to the use of bioenergy in the national energy system [11]. In this context, a system-wide approach allows identifying the most cost-efficient strategies on an overall societal level to meet GHG emission reduction targets, while addressing complex dynamic relationships between subsectors of the national energy system (e.g. competition between biomass feedstock and energy sources) and avoiding sub-optimized solutions [12].

In particular, optimization models of integrated energy systems have been used to study the future role of bioenergy in different national contexts, namely through multiple scenario analysis. Börjesson et al. [12] used a TIMES model to analyze the long-term role of liquid biofuels in the Swedish energy system under several policy scenarios: GHG mitigation targets, renewable electricity production and phase-out of fossil fuels for road transportation. Similarly, Zhao et al. [13] conducted a scenario-based analysis on the future role of liquid biofuels in China using a TIMES model in order to address uncertainties on the availability of marginal land, agricultural and forestry residues, feedstock prices and conversion technology progresses. Combining a TIMES energy model and the CARD agriculture model for the United States, Dodder et al. [14] studied alternative scenarios on fossil fuel prices and cellulosic biomass availability and their impacts on biofuel markets and the energy-agriculture systems in general. A TIMES model of the bioenergy sector was used by Hugues et al. [15] to better understand the dynamics of the biofuel industry in France under GHG mitigation scenarios. Panos and Kannan [16] analyzed the penetration of bioenergy in stationary applications using a Swiss TIMES model for electricity and heat in various scenarios on the electricity and heat demands, international energy prices, biomass resources, and GHG mitigation options. Using an energy system model TIMES for Germany, König [17] assessed the role of bioenergy options to reach different energy and environmental targets.

While similar conclusions can be derived from these studies (e.g. the future role of liquid biofuels as a GHG mitigation option in the transportation sector), most of the outcomes vary significantly: 1) across countries due the intrinsic characteristics of the energy system, geographical conditions and resources availability, and 2) across scenarios given the large number of assumptions on uncertain parameters. Consequently, we propose an original application of an optimization TIMES model to study the role of bioenergy in a different context: a Canadian province already characterized by a carbon free (at 97%) electricity sector with huge hydro potential, abundant forest resources and ambitious GHG mitigation targets.

The main objective of this paper is indeed to explore the role of bioenergy in transition scenarios toward a low-carbon energy system for the province of Quebec up to 2030. In particular, this paper aims at analyzing the economic feasibility of second-generation biofuels and evaluating how climate policies would affect the development of the bioenergy industry in Quebec. Our research will benefit this industry by providing an economic analysis in a regional Canadian context and helping identify key measures that will favor a transition towards a more sustainable energy future, with more renewable fuels. Such a transition should improve the resilience of the energy system and economy as well as the quality of its environment. As such, our analysis is also of interest for the provincial government, who just released its 2030 energy policy in which a target of 50% increase in bioenergy production is set.

Our analysis relies on NATEM (North American TIMES Energy Model) [6] a model describing the Canadian energy sectors using the TIMES modeling approach of the International Energy Agency [18]. It considers a varied and exhaustive number of parameters to optimize energy development scenarios that are framed by legislative policies, such as limits on GHG emissions. In this article, NATEM provides for the Province of Quebec an economic assessment of the future deployment of bioenergy under four levels of GHG emission reduction targets.

The paper is organized as follows. Section 2 briefly introduces the NATEM model and the most relevant input assumptions. Section 3 presents the different scenarios modeled. Section 4 consists of an overview of the main results in terms of GHG emissions, energy profiles and mitigation costs. Section 5 contains a brief sensitivity analysis on these results and a comparison of results with the literature. Finally, Section 6 concludes with a summary of key points, limitations and future works.

2. Methodology

2.1. The NATEM energy model

NATEM is a particular implementation of the TIMES modeling approach for Canada.[1] This methodology is well established, being currently used in about 70 countries around the world, and has already been described in numerous peer-reviewed papers while the full documentation is publicly available [18]. In short, TIMES follows a techno-economic modeling approach to describe the energy sector of a given region or country, accounting in particular for a variety of specific energy technologies modeled through both technical parameters (including emission coefficients) and economic parameters. TIMES offers thus a detailed representation of an energy sector, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials. It simulates market competition of energy carriers and energy technologies to satisfy useful energy demands specified exogenously over a given time horizon.

TIMES is cast as a dynamic linear programming model,[2] and as such contains 3 components: objective function, variables, and constraints. The first component (objective) corresponds to minimizing the net total discounted cost of the entire energy system. Assuming that energy markets are under perfect competition, this cost minimization is equivalent to maximizing the sum of energy consumer and producer surpluses, and simulates energy market equilibrium. The second component (variables) corresponds mainly to future investments and activities of technologies at each time period, amount of energy produced or consumed by technologies, as well as energy imports and exports. An additional output of the model is the implicit price (shadow price) of each energy form, material and emission. The third component (constraints) corresponds to various limits (e.g., amount of energy resources available) and obligations (e.g., energy balances throughout the system, useful energy demand satisfaction) to be respected. Finally, TIMES acknowledges that demands for energy services (useful demands) are elastic to their own prices. This makes possible the endogenous variation of demands in policy scenarios compared to the baseline, thus capturing behavioral changes and their impacts on the energy sector.

The NATEM model is a specific application to the 13 Canadian

[1] For clarity, this means that NATEM is a TIMES model, with a specific database that reflects the Canadian energy situation.

[2] TIMES is intended to be used as a strategic decision support tool (e.g., to identify energy sectors that will be impacted by a given policy), and not a tactical decision tool to operate specific energy facilities. In that respect, the linear functional forms used in TIMES do provide useful information, albeit at the expense of a simplified view of (input/output) relations within the energy sector.

provinces and territories as well as inter-jurisdictional flows of energy and material commodities [6]. The model database describes 475 such commodities in each jurisdiction, as well as more than 4500 explicit technologies. NATEM is driven by 70 end-use demands for energy services, projected to the 2050 horizon. This projection relies on 9 time periods of variable length, shorter at the beginning (1–2 years) and longer (5 years) at the end of the horizon. Besides, each time period is divided into and 16 annual time slices (4 seasons a year and 4 intraday periods). In NATEM, all costs are expressed in 2011 Canadian dollars ($) and the global annual discount rate has been set to 5%.

2.2. The bioenergy sector

The NATEM database includes a large number of existing and emerging technologies for all Canadian regions. This section describes more specifically the different bioenergy pathways and the assumptions related to the relevant processes. NATEM represents complete supply chains with a clear representation of three types of entity: 1) technologies or processes (feedstock production, transport, transformation, conversion in biorefineries), 2) commodities (feedstock, final products, by-products), and 3) energy flows between technologies and commodities. Each process is modeled as a given technology and characterized by its technical parameters (useful life, efficiency, availability factor, etc.) and economic parameters (investment and operation costs, etc.). Consequently, NATEM enables to account for the effect of Canadian policies on the role of bioenergy in the near- and long-term future.

While our approach brings valuable insights regarding the role of bioenergy in transition scenarios toward a low-carbon energy system by covering the entire energy system, there are also important limitations to raise. The role of bioenergy is assessed solely from the perspective of mitigation options for energy-related GHG emissions. The current version of the model does not capture the potential impacts on non-energy related GHG emissions that could arise from an increasing demand for biomass feedstock and land use changes. Moreover, we do not capture environmental impacts other than climate, such as water resources, biodiversity, health, etc. Finally, we assume a biogenic carbon neutrality principle at the final end-use level. This remains a controversial principle according to which an equivalent amount of CO_2 is sequestered from the atmosphere by growing biomass. Consequently, we cannot consider that these bioenergy commodities meet the most stringent sustainability criteria as those suggested by the European Union [19].

2.2.1. Resources

Several categories of feedstock are considered for the production of various types of bioenergy and several usages are in competition for this bioenergy (Table 1). They are characterized by their maximal annual availability and their supply costs; the cost of conversion processes is introduced in Table 2. The amount of feedstock from agricultural crops such as corn for ethanol production and soybeans (and other fatty materials) for biodiesel production remains limited by the availability of agricultural land as well as food and feed requirements [20]. Similarly, the amount of fatty residues for first-generation biodiesel production is not likely to increase much in the future. In Quebec, there is no limit on the amount of first-generation biofuels that can be part of the transportation fuel mix. However, we specified the maximum amount of crop feedstock available to supply these first-generation biofuels taking into account the need of the Canadian population for food production. Consequently, these crop feedstocks could produce a maximum amount of approximately 15 PJ of first-generation ethanol and 11 PJ of first-generation biodiesel without affecting the food supply for Canadians.

However, significant amounts of forest biomass are available for the production of second-generation biofuels or syngas, for direct use in residential and commercial heating systems, for power generation and for use in the pulp and paper industry. A portion of the forest biomass comes from existing harvesting activities and includes trunks, crowns and branches on public land. Merchant woods, stumps and roots are not included. The more conservative estimation represents a potential of 137 PJ, while the less conservative potential estimation reaches 174 PJ [21]. This additional quantity (37 PJ) is included in the database at a higher supply cost. An additional amount of unharvested biomass is also available annually (416 PJ), not including branches and foliage. This quantity is derived from the volumes of all commercial timber species (stem only), which were not harvested during the forestry period of 2008–2013 [21]. A maximum and arbitrary 15% of this amount is included in the database for energy production at a significantly higher supply cost as new collection and transport infrastructure are required. Other potential sources of biomass were not included in the database: biomass from areas affected by insects and fires, and reforested agricultural areas.

Agricultural residues, industrial residues, and dedicated crops (fast-growing trees for energy production) also provide significant amounts of cellulosic feedstock [22–25]. Finally, various sources of organic matter are available from municipal waste, manure, sewage sludge, and biogas captured at landfill sites [26–29].

In most cases, these estimations (Table 1) correspond to the amount of primary energy available in each category of feedstock. The amount of bioenergy produced and available for final consumption (biofuels, renewable natural gas, etc.) depends on the efficiency of conversion processes (Section 2.2.2). Only the potential associated with agriculture crops for first-generation biofuels (corn, wheat, other starches, soybeans, canola and greasy residues) already account for conversion efficiency losses.

The availability of feedstock is restricted to the borders of each jurisdiction. We assume that each jurisdiction cannot import biomass feedstock from neighboring jurisdictions, given the uncertainties about the adoption of more ambitious GHG reduction targets in other provinces and regional competition for the available feedstock. However, the bioenergy commodities produced from these feedstocks can be traded across jurisdictions. These issues are beyond the scope of this analysis. International imports and exports of first-generation biofuels are fixed at existing 2011 levels. International imports and exports of feedstock are not considered.

Cost estimations include costs for production, preparation and transport of feedstock. For municipal waste, this does not include the cost of selective collection of organic matter, as municipalities are already forced to implement it. Similarly, some biogas already captured from landfills is available at a very low cost, while an additional amount is available provided that an important investment is made to build a collection network.

We assume that the concept of biogenic CO_2 neutrality applies to all forms of bioenergy at the final end-use level and remains valid throughout the time horizon. This means that the combustion of bioenergy in end-use devices does not lead to any CO_2 emissions as it is assumed that an equivalent amount of CO_2 is sequestered from the atmosphere during biomass growth. The carbon neutrality concept does not apply to the whole supply chain as an important amount of energy is burned in conversion processes. In addition, we do not account for the whole life cycle emissions of any form of bioenergy (e.g. emission sources located outside the model boundary, which is Canada).

2.2.2. Conversion processes

NATEM includes all existing first-generation ethanol and biodiesel plants, as well as second-generation biofuel plants. Ethanol production is primarily based on the fermentation of corn and wheat. The total production capacity is approximately 40 PJ per year for Canada, which is equivalent to approximately 1.8 billion litres of ethanol per year (2.8 PJ or 125 million litres in Quebec) [30]. Biodiesel production is based on the transesterification of soybeans and canola. The total production capacity is approximately 23.4 PJ per year for all Canada, which is

Table 1
Annual availability of resources for bioenergy production.
Source: [20–29]

Type	Average costs $/GJ	Maximal limit 2011 PJ/yr	Conversion technology 2050 PJ/yr	Bioenergy	Final use	
Corn	23.42	10.09	11.21	Fermentation	Ethanol 1st gen	All sectors
Wheat	23.42	0.74	0.83	Fermentation	Ethanol 1st gen	All sectors
Others starch	28.84	3.79	4.21	Fermentation	Ethanol 1st gen	All sectors
Soybean	26.65	6.00	10.00	Transesterification	Biodiesel 1st gen	All sectors
Canola	21.22	0.01	0.03	Transesterification	Biodiesel 1st gen	All sectors
Greasy residues	2.36	2.77	4.16	Transesterification	Biodiesel 1st gen	All sectors
Forest residues				Combustion	Solid biomass	All sectors
				Direct use	Solid biomass	Pulp and paper
				Densification	Pellets	Electricity Residential heating
	7.50	138.35	138.35	Enzymatic hydrolysis	Cellulosic ethanol	All sectors
	11.25	41.50	41.50			
	22.50	62.26	62.26	Gasification	FT diesel	All sectors
				Gasification	Syngas	All sectors
				Gasification	Biojet	Transport – Aviation
				Gasification	Electricity	All sectors
				Combustion	Solid biomass	Electricity
Dedicated crops (fast-growing trees for energy production)				Densification	Pellets	Electricity Residential heating
	14.34	4.81	4.81	Enzymatic hydrolysis	Cellulosic ethanol	All sectors
	28.68	1.20	1.20	Gasification	FT diesel	All sectors
				Gasification	Syngas	All sectors
				Gasification	Biojet	Transport – Aviation
Agriculture residues				Densification	Pellets	Electricity Residential heating
	8.67	22.90	22.90	Enzymatic hydrolysis	Cellulosic ethanol	All sectors
	17.35	32.10	32.10	Gasification	FT diesel	All sectors
				Gasification	Syngas (renewable natural gas)	All sectors
				Gasification	Biojet	Transport – Aviation
Industrial residues				Enzymatic hydrolysis	Cellulosic ethanol	All sectors
				Gasification	FT diesel	All sectors
	7.88	21.87	21.87	Gasification	Syngas (renewable natural gas)	All sectors
	15.77	32.80	32.80			
				Gasification	Biojet	Transport – Aviation
Municipal organic waste	2.50	86.50	86.50	Thermochemical platform	Biomethanol	Transport
				Anaerobic digestion	Biogas-Biomethane (renewable natural gas)	All sectors
				Direct use	Electricity	All sectors
Biogas (landfill)	1.00	39.10	39.10	Anaerobic digestion	Biogas- Biomethane (renewable natural gas)	All sectors
	10.00	72.60	72.60	Direct use	Electricity	All sectors
Manure	3.50	52.10	52.10	Anaerobic digestion	Biogas- Biomethane (renewable natural gas)	All sectors
				Direct use	Electricity	All sectors
Sludge	2.50	5.80	5.80	Anaerobic digestion	Biogas- Biomethane (renewable natural gas)	All sectors
Pulp and paper residues	7.00	0	10.69	Biological conversion + Kraft plant	Butanol	Transport

equivalent to about 670 million litres of biodiesel per year (2.1 PJ or 60 million litres in Quebec) [30]. The production capacity of wood pellets is also represented by densification technologies, with a capacity of 9.4 PJ in 2011 and 4.5 PJ of additional capacity in 2015 [31]. About 5% of pellet production is exported to the United States, 63% to the rest of the world, and the remaining 32% is consumed locally.

NATEM includes existing capacities for electricity generation from municipal wastes and biogas from landfill sites. Similarly, the model includes existing biomethane production capacities, such as the anaerobic digester at St-Hyacinthe (Quebec) which operates using organic materials from municipal selective collection and whose gas will be injected shortly in the natural gas network. The installed capacity in 2015 is only 0.5 PJ for the Province of Quebec.

Many new technologies are available in NATEM for future investments, including technologies currently available on a commercial scale as well as emerging technologies that can use a wide variety of biomass: Fischer-Tropsch gasification process (syngas, FT diesel, aircraft biojet) and enzymatic hydrolysis (cellulosic ethanol) (Table 2). Plants that are currently under demonstrations are also included, such as the Enerkem plant in Edmonton (Alberta) producing biofuels from organic waste, the Enerkem gasification plant in Sherbrooke (Quebec) producing biofuels from various sources of wood biomass and the enzymatic hydrolysis plant in Ottawa (Ontario) producing cellulosic ethanol from agricultural residues.

The database also includes options for investment in biomethane (or renewable natural gas) technologies from organic municipal waste or

Table 2
Conversion technologies for bioenergy production.
Source: [29,32–35]

Technology	Source	Eff %*	Inv cost ($/kW)	Operation costs ($/kW)	PJ electricity /PJ source	PJ thermal / PJ source
Transesterification- Biodiesel 1st gen	Vegetal oil Greasy residues	44.0%	180.73	18.1	0.003	–
Fermentation – Ethanol 1st gen	Cultures - Starch / Sugars	29.0%	237.44	23.7	0.1	0.20
Gasification– Syngas (or renewable natural gas)	All types of woody biomass	93.0%	1160.00	116.0	0.03	0.02
Gasification– FT diesel		64.5%	1520.00	152.0	0.03	0.02
Gasification– Biojet		60.0%	1672.00	167.20	0.03	0.02
Gasification- Bio-methanol		61.0%	1160.00	116.0	0.03	0.02
Anaerobic digestion – Biogas	Manure and slurry	38.0%	736.99	55.83	0.03	0.02
	Organic materials	36.0%	1875.98	167.50	0.01	0.02
	Agricultural residues	34%	736.99	55.83	0.03	0.02
Biogas upgrade into bio-methane (or renewable natural gas)	Manure and slurry	62.0%	702.1	205.1	0.01	–
	Organic materials	78.4%	498.6	237.5	0.01	–
	Agricultural residues	62.0%	702.1	205.1	0.01	–
Enzymatic hydrolysis – Cellulosic ethanol	Woody biomass	41.0%	953.83	95.4	0.00	–
Biological conversion + Kraft plant	Woody biomass	92.0%	326.94	19.00		0.3

* In most cases, efficiency estimates were developed by our research team based on specific studies and adapted to the Canadian context. They tend to represent very conservative estimates. In particular, waste systems could have conversion efficiencies up to 90%.

manure. Anaerobic digesters first produce biogas, which has to be purified and converted to biomethane before it is injected into the conventional natural gas transmission network (gas pipelines) or used directly to heat buildings or as fuel.

2.2.3. End-use technologies

A large number of end-use devices in all sectors can use bioenergy (Table 1). First generation ethanol and cellulosic ethanol can be used in all sectors as a replacement of gasoline in a maximum proportion of 10% due to different fuel properties. This includes off-road and road vehicles, rail and marine transportation technologies, space heating devices in the residential, commercial and agriculture sectors, as well as industrial technologies. Flex fuel cars can take up to 85% ethanol. Biomethanol can replace gasoline at a maximum of 10% in road vehicles.

Similarly, first generation biodiesel can be used in all sectors as a replacement for diesel in a maximum proportion of 5%. However, heavy trucks can use up to 35% of biodiesel by 2050; this rate is also used as the maximum for marine transportation. This theoretical maximum for 2050 is very optimistic given that the maximum concentration is currently limited to 10% for a portion of the year in Canada (during cold weather down to $-29\,^{\circ}C$) but could be increased to 20–40% during milder periods [36]. In addition, FT diesel can be used as an alternate fuel at 100% due to its similar properties with conventional diesel. Biojet and butanol can be used as a replacement for conventional jet fuel for aircraft at a maximum proportion of 50% for security reasons. Butanol can be used at 100% as an alternate fuel for gasoline road vehicles since this segment is less constrained by security rules than aviation.

Renewable natural gas (syngas and biomethane) can be used as a replacement for conventional natural gas in all sectors. Biogas from landfill can also be used to produce electricity. Solid biomass is available for space heating, electricity generation and for the pulp and paper industry. Wood pellets are available for space heating and electricity generation.

3. Scenarios

As a specific case study to explore the role of bioenergy in the energy transition, we analyze several scenarios[3] for the Province of Quebec. From a reference scenario, four GHG emission reduction scenarios are derived based on different targets to be reached by 2030:

- **REF**: The reference scenario represents a business-as-usual case without any limit on GHG emissions or technological constraints.
- **GHG1**: A less stringent scenario arbitrary set to a 10.0% reduction by 2030 compared to 1990 levels.
- **GHG2**: A scenario with a reduction target of 25.9% by 2030 compared to 1990 levels, which corresponds to the current Quebec target for 2030 assuming that a portion of the reductions is done outside the jurisdiction through carbon credit purchases.
- **GHG3**: A scenario with a reduction target of 37.5% by 2030 compared to 1990 levels, which is the current Quebec target for 2030 if all reductions are achieved domestically.
- **GHG4**: A more stringent scenario arbitrary set to a 40.0% reduction by 2030 compared to 1990 levels.

The gradual increase in the emission reduction targets allow for a better understanding of the effects of climate policies on the penetration rates of different forms of bioenergy.

3.1. Reference scenario

The reference scenario (REF) represents the evolution of the energy system in a business-as-usual context. From the 2011 base year, demands for energy services are projected through 2030 using a coherent set of socio-economic assumptions from the Canadian Energy System Simulator model [5,20]. This latter model is calibrated with historical data for the period 1978–2010 and uses projections of the National Energy Board [37]. The main assumptions characterizing the socio-economic context are: i) a Canadian GDP that is expected to grow by 47.5% between 2011 and 2030, ii) an average annual population growth rate of 0.98% for the same period, iii) an average annual GDP per capita growth rate of 1.86%.

Moreover, this reference scenario includes government policies already in place such as: the 2013–2020 Action Plan on Climate Change for Quebec [38], the Quebec Transport Electrification Action Plan [39] and its objective of reducing the amount of fuel consumed annually in Quebec by 66 million litres, Corporate Average Fuel Economy (CAFE)

[3] Please note that the scenarios we present are not predictions (forecasts) of what the future may bring, but rather visions of possible futures based on coherent sets of hypotheses.

Table 3
GHG emission reduction targets for the energy sector in Quebec.

Target	% reduction in 2030 from 1990 levels	Cap in Mt in 2030	Absolute reduction in Mt in 2030 from 1990 levels
GHG1	− 10.0%	52.7 Mt	− 5.9 Mt
GHG2	− 25.9%	43.4 Mt	− 15.2 Mt
GHG3	− 37.5%	36.6 Mt	− 22.0 Mt
GHG4	− 40.0%	35.1 Mt	− 23.4 Mt

standards [40], federal and provincial regulations on the minimum content of renewables in all the gasoline (5%) and diesel (2%) sold in Canada [41], as well as the existing carbon market with California through a floor price ranging from \$9.9/tonne in 2012 to \$24.9/tonne in 2030 (in CAD \$2011), an annual increase of 5%.

3.2. Reduction scenarios

NATEM covers a majority of GHG emissions coming from fuel combustion and fugitive sources in the energy sector that is responsible for 66% of Canadian emissions in 1990 (58.6 Mt CO_2-eq) and 69% in 2013 (56.3 Mt CO_2-eq) [42]. NATEM currently excludes emissions from agriculture (other than from combustion of energy), industrial processes, and waste. The analysis shows the role of bioenergy in long-term decarbonization scenarios of the energy sector only. This is an important limitation of our study as energy crops and the agriculture sector in general can be an important source of GHG emissions. Future works will allow to analyze the impacts of integrating GHG emissions from non-energy sectors as well.

The translation of emission reduction targets into absolute limits of GHG emissions is shown in Table 3; the constraint on emissions is interpolated linearly between 2015 and 2030. In addition, all emission reduction scenarios include targets from other Canadian jurisdictions (Table 4).

4. Result analysis

In this section, we present for each scenario the optimal solutions computed by NATEM for Quebec in terms of GHG emissions, configuration of the energy system and mitigation costs.

4.1. GHG emissions

In the REF scenario, GHG emissions increase by 8% between 2011 and 2030 (Fig. 1). The dip observed in 2025 is caused by a higher penetration of electric vehicles for passenger transport as they become competitive with conventional vehicles. The reduction in emissions is afterward offset by an increase in demand. Achieving GHG emission reduction targets implies reductions of 18% (GHG1), 32% (GHG2), 43% (GHG3), and 45% (GHG4) in 2030 compared to the reference.

The breakdown of emissions by sector (Fig. 2) shows that

Table 4
GHG emission reduction targets for the energy sector in Canada.

Jurisdiction	Target*	Target year	Reference year
Canada	− 30%	2030	2005
British Columbia	− 18%	2020	1990
Alberta*	+ 40%	2020	1990
Saskatchewan*	+ 21%	2020	1990
Manitoba	− 33%	2030	2015
Ontario	− 37%	2030	1990
New-Brunswick	− 10%	2020	1990
Northwest Territories	− 10%	2020	1990

* A positive "reduction target" corresponds to limiting GHG emission growth from the reference year.

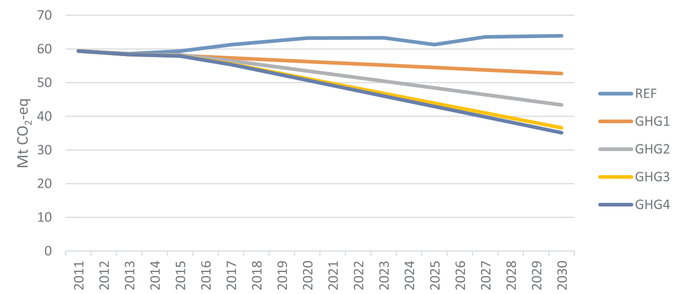

Fig. 1. Total GHG emissions from the energy sector in Quebec.

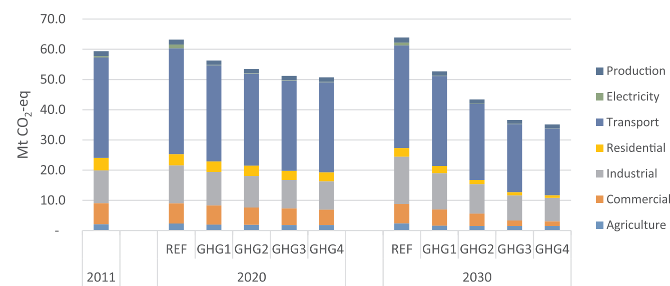

Fig. 2. GHG emissions by sector in Quebec.

transportation is the most emitting sector in the reference scenario, with more than 50% of total emissions over the horizon, caused by a continued reliance on petroleum products to meet long-term energy service demands. Emissions from industries represent 25% of the total in 2030. In GHG scenarios, reductions mostly stem from the transport sector where GHG emissions decrease from 34.0 $MtCO_2$-eq in 2030 in the REF scenario to 22.0 $MtCO_2$-eq in the GHG4 scenario. This reduction accounts for 40% of the total reduction needed to achieve the target.

4.2. Overview of final energy consumption

Fig. 3 illustrates the final energy consumption by fuel in Quebec. In the REF scenario, final energy demand is projected to increase by 5% between 2011 and 2030, a lower increase than the Canadian average (16%). In Quebec, final energy is mainly consumed by industries (37%) and the transport sector (29%); these proportions do not change significantly over time or across scenarios. The industrial sector shows the highest growth and is responsible for the majority of the additional demand between 2011 and 2030. The energy mix continues to be dominated by petroleum products and electricity in the long term, representing 40% and 41% of total consumption in 2030, respectively.

In order to achieve the GHG emission reduction targets, final energy consumption should be reduced by 2–3% depending on the scenario

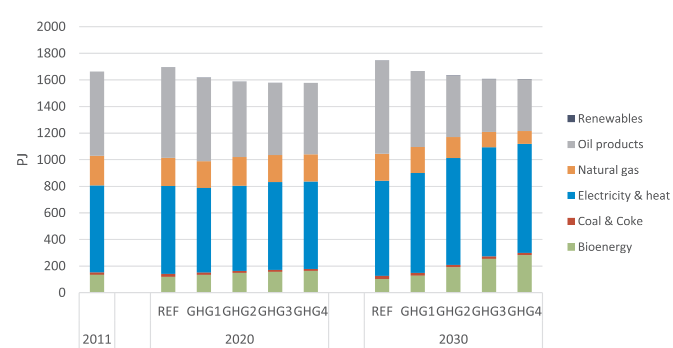

Fig. 3. Final energy consumption by fuel in Quebec. *Renewables include decentralized geothermal and solar energy of the residential and the commercial sectors.

(GHG2 to GHG4) between 2011 and 2030. Here, important transitions take place in the energy system, in particular: i) an endogenous reduction of demands for energy services due to price elasticity, especially for air and marine transport (up to 13% compared with their projected initial value for 2030); ii) energy efficiency improvements through technological substitutions; iii) greater penetration of electricity in all sectors (between 45% and 51% of the total consumption in 2030) at the expense of oil (from 40% in the REF scenario to 24% in the GHG4 scenario) and natural gas (from 12% in the REF scenario to 6% in the GHG4 scenario); iv) a greater reliance on bioenergy in 2030 (with a share increasing from 6% in the REF scenario to 18% in the GHG4 scenario). Moreover, liquefied natural gas (LNG) and renewable natural gas (syngas and biomethane) replace a portion of conventional gas: while conventional gas goes from 224 PJ in 2011–75 PJ in the most stringent scenario (GHG4), a 67% decrease, LNG and renewable natural gas consumption reaches 21 PJ and 94 PJ, respectively. The combined decrease for all forms of gas is therefore 15%.

4.3. Overview of primary energy production

Primary energy production in Quebec relies heavily on the exploitation of hydroelectricity and biomass feedstock resources (Fig. 4). Other renewable resources (labeled ‘Renewable’ in Fig. 4) include wind energy produced from existing wind farms or already scheduled for future construction, as well as new investments in decentralized solar energy. Not that the primary production mix in the Province of Quebec, already low in GHG emissions, is very different from that of Canada as a whole, where fossil fuels of the Western Canadian Sedimentary Basin (WCSB) dominate the production mix.

4.4. Overview of energy trade

The Province of Quebec is a net exporter of electricity and oil products coming from its two refineries (Fig. 5). Activities in these later two facilities are, however, reduced in order to meet emission reduction targets, and slightly more oil products are imported since this is cheaper than abating emissions from refining activities. However, an additional portion of unconsumed oil products in Quebec is exported and partially offsets this decrease.

Quebec is a net importer of oil, gas and coal. Indeed, although shale gas and shale oil reserves have been located on the Anticosti Island, their exploitation through hydraulic fracturing is controversial and has been put on hold by the current Quebec government. Consequently, Quebec imports all the crude oil used for its two refineries. While most of the imports come from international markets in 2015, they are gradually replaced with synthetic oil from Alberta (Canada) given a lower price for oil sands. As for natural gas, imports are also decreasing to meet the emission reduction targets. Natural gas is imported from Alberta using existing pipelines. However, a larger amount could be imported from the United States with the rise of its shale gas production.

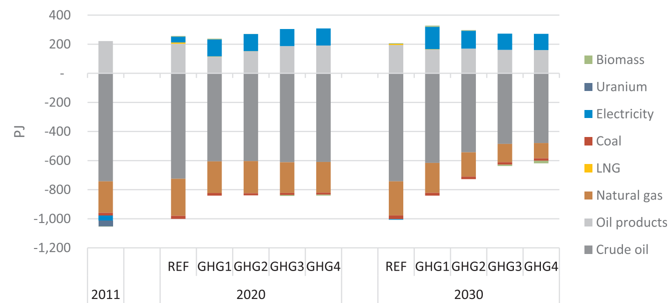

Fig. 5. Net exports to Canadian and international destinations.

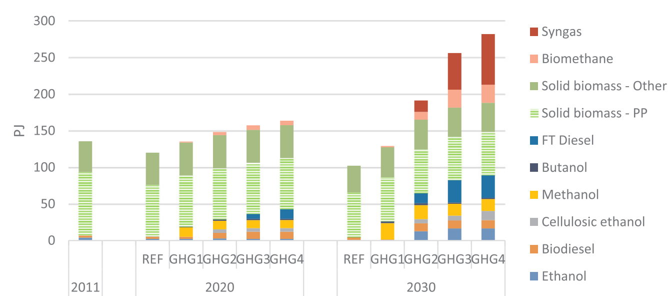

Fig. 6. Bioenergy consumption by type in Quebec.

4.5. Role of bioenergy

Bioenergy includes a wide variety of liquid, solid and gaseous fuels (Fig. 6). Liquid biofuels are part of the energy mix in Quebec starting from 2020 in the most stringent reduction scenarios with 10 PJ of biodiesel, 2 PJ of ethanol, 7 PJ of cellulosic ethanol, 11 PJ of methanol, 2 PJ of butanol and 13 PJ of FT diesel. By 2030, the total amount of liquid biofuels reaches 89 PJ in the GHG4 scenario. However, renewable natural gas becomes competitive on a longer time frame, with 25 PJ of biomethane and 69 PJ of syngas in 2030 in GHG4 (total of 94 PJ). In 2030, syngas becomes the second most important form of bioenergy after solid biomass in GHG3 and GHG4. Renewable natural gas can be transported into the existing gas pipeline network and thus serve as a replacement for natural gas in many sectors. The total amount of solid biomass represents about 60 PJ in the pulp and paper (PP) industry by 2030 in all scenarios and between 37 PJ and 40 PJ in the other sectors. While the total amount remains relatively constant across scenarios, there is a switch in the type of usage across scenarios: a portion of the biomass used for space heating in the REF scenario is used in industrial sectors in GHG emission reduction scenarios (see below).

The various forms of bioenergy play a major role in satisfying several energy service demands while reducing GHG emissions; their role becomes increasingly important in all sectors as the emission reduction target becomes more ambitious (Fig. 7).

While electrification represents a central option to decarbonise passenger transportation, especially for personal car and light truck segments, a significant proportion of biofuels is used in plug-in hybrid

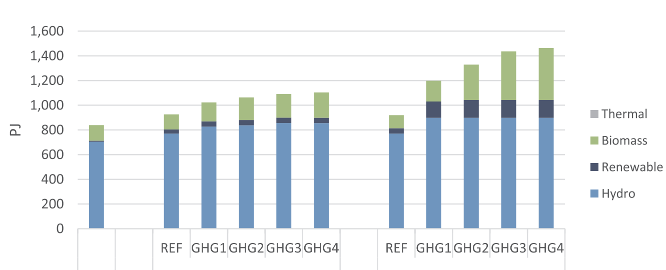

Fig. 4. Primary energy consumption by type in Quebec.

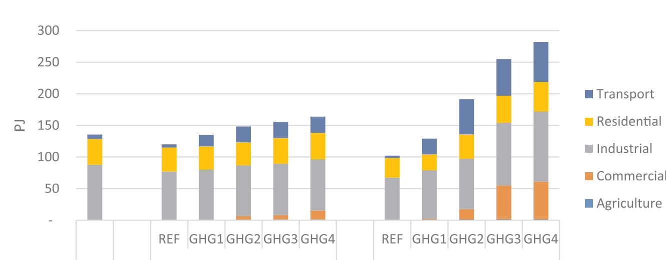

Fig. 7. Bioenergy consumption by sector in Quebec.

vehicles: up to 28 PJ in 2030 in the most stringent scenario (GHG4). As for freight transportation, a portion of diesel consumption is replaced with biofuels and renewable natural gas (together with compressed natural gas in small amounts for medium and light trucking, and LNG primarily for marine transportation and to a small extent for heavy trucking).

In the residential, commercial and agriculture sectors, solid biomass and liquid biofuels meet a portion of the space heating requirements and commercial vehicle fleets: up to 64 PJ in the GHG3 and GHG4 scenarios (11% of total energy consumption in these sectors). Moreover, up to 69% of natural gas consumption is replaced with renewable natural gas in the GHG4 scenario, representing 8% of the total consumption of these sectors.

In the industrial sector, bioenergy consumption follows two opposite trends. One the one hand, biomass consumption generally decreases over time, about 18% between 2015 and 2030 in the REF scenario and between 7% and 9% over the same period in the GHG reduction scenarios. This decrease is due to the projected decline in the demand for pulp and paper over time. But part of this reduction is offset by the use of biomass as an alternative to coal in the cement and copper industries to reduce GHG emissions: while its consumption remains around 6 PJ over the time horizon in the REF scenario, it increases up to 16 PJ in 2030 in all GHG reduction scenarios. One the other hand, a fraction of conventional natural gas is replaced with renewable natural gas (24% in GHG3 and 36% in GHG4), while the proportion of natural gas (both conventional and renewable) remains relatively constant over time and between scenarios (from 21% in 2011 to 19% in the REF scenarios and 16% in scenarios GHG2 to GHG4).

Since most conversion processes have low efficiency, a large amount of feedstock is needed to produce the various types of bioenergy (Fig. 8). In 2020, forest residues remain the most important source of bioenergy with 67–94% of the total feedstock depending on the scenarios. Municipal waste is the second most important source with up to 17% of the total. Landfill biogas accounts for a maximum of 10% while all the other feedstock sources remain marginal. In 2030, the mix is more diversified with 43% of forest residues for GHG4, 13% of industrial residues, 12% manure, 9% landfill biogas, 8% municipal waste, 5% agriculture residues and a small proportion of all the other types of feedstock. Table 5 compares the feedstock used for bioenergy production in 2030 across scenarios (same numbers used for Fig. 8) with the maximum potential available annually. For some feedstocks, a supply curve was included in NATEM with different quantities available at a given cost (see columns Max 1, Max 2 and Max 3). For instance, for forest residues, the supply curve includes 3 steps.

The maximum amount of feedstock available to produce first-generation biodiesel and ethanol (soybeans, canola, etc.) is used in 2030 under the two most stringent reduction scenarios (GHG3 and GHG4). The first amount of forest biomass available at a lower cost and related to existing harvesting activities (138 PJ) is reached in 2030 for scenarios GHG2 to GHG4. The additional quantity of biomass available at a higher cost is also totally required in 2030 in GHG3 and GHG4 (close to 180 PJ). Nevertheless, non-harvested biomass available at a significantly higher cost is not part of any optimal solutions.

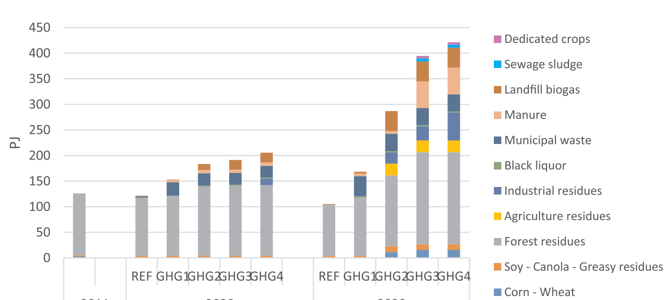

Fig. 8. Feedstock used for bioenergy production in Quebec.

Only 42% of the maximum potential from agricultural residues is used in scenarios GHG2 to GHG4 by 2030 (but 100% of the first quantity), mainly for the production of syngas, but also of second-generation biofuels. The first quantity of industrial residues is used to the maximum in scenarios GHG2 to GHG4 by 2030, while the second quantity available at a higher cost is used only in GHG3 and GHG4 mainly for the production of second-generation biofuels.

The amount of organic matter contained in municipal waste is used at the maximum potential (between 39% and 46%) in 2030 for the production of biomethane, while animal manure, landfill biogas (Max 1) and sewage sludge are used at 100%. Installing an additional biogas capture network in landfills does not appear a cost-effective option based on our assumptions.

4.6. Mitigation costs

The marginal cost of abatement increases rapidly with the level of reduction (Fig. 9), reaching in 2030: \$258/tCO_2-eq (GHG1), \$414/tCO_2-eq (GHG2), \$576/tCO_2-eq (GHG3) and \$581/tCO_2-eq (GHG4). The tax level associated with scenarios GHG3 and GHG4 would correspond, for instance, to almost doubling the actual gasoline price. It is possible, however, that the price elasticity assumptions in the model underestimate the reduction in energy service demands. While the first tons of GHG can be reduced at a much lower cost, and even at a negative cost in some cases (some energy conservation or energy efficiency measures are cost-effective even without mitigation policies), the reduction options become more expensive as progress is achieved and the least costly options are adopted.

The total net discounted cost of the energy system for the next 15 years (2015–2030) increases compared to the REF scenario by 1.8% (GHG1), 4.3% (GHG2), 6.7% (GHG3) and 7.0% (GHG4). These costs correspond respectively to 0.7%, 1.6%, 2.4% and 2.6% of projected GDP by 2030.

5. Discussion

5.1. Sensitivity analysis

As seen in Section 4.5, the production and use of bioenergy in Quebec is not limited by the amounts of feedstock available for achieving the 2030 target, but rather by the costs of the supply chain. Remaining quantities of feedstock could be recovered, but at higher costs. A sensitivity analysis was performed to see what would be the impacts of having access to a greater amount of feedstock at competitive costs: the cost of unharvested forest residues (representing 62 PJ of unused feedstock) was arbitrarily reduced by 30–50%. Results are displayed in Fig. 10.

From a cost reduction of 40%, unharvested forest residues become competitive as a feedstock, and its maximum potential is used by 2030 (+62 PJ); refer to Table 5 for the maximum potential. This is done at the expense of manure, for which the second step of the supply curve is not used anymore (−27 PJ). The total amount of bioenergy available in the system increases from 256 PJ in GHG3 to 276 PJ with a cost decrease of 40% and more (GHG3 – 40% and GHG3 – 50%). Forest residues are mainly used to produce syngas to be used in the industrial sector as a replacement for conventional gas. While syngas represented 20% of the total amount of bioenergy in GHG3, it reaches 28% in the scenarios GHG3 – 40% and GHG3 – 50%. This additional amount of syngas in the system slightly reduces the need for other types of bioenergy such as biomethane (10–7%), solid biomass (24–22%) and FT diesel (12–10%).

5.2. Comparison of results

Some recently published studies present a prospective overview of

Table 5
Feedstock potential available and used by 2030.

2030	Available potential			Feedstock used					%
PJ	Max1	Max2	Max3	REF	GHG1	GHG2	GHG3	GHG4	GHG4
Corn - Wheat	15			0	0	11	15	15	100%
Soy - Canola - Greasy residues	11			3	3	11	11	11	100%
Forest residues	138	180	242	101	115	138	180	180	74%
Agriculture residues	23	55		0	0	23	23	23	42%
Industrial residues	22	55		0	0	22	28	55	100%
Black liquor	5			0	2	3	2	2	35%
Municipal waste	87			0	39	34	34	34	39%
Manure	52			0	5	5	52	52	100%
Landfill biogas	39	112		1	3	39	39	39	100%
Sewage sludge	6			0	0	0	6	6	100%
Dedicated crops	5	6		0	0	0	5	5	100%

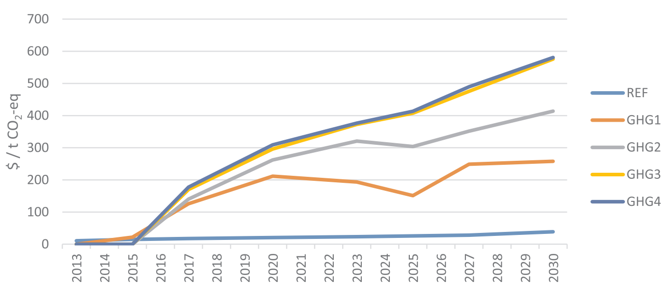

Fig. 9. Marginal abatement cost for one ton of CO_2-eq.

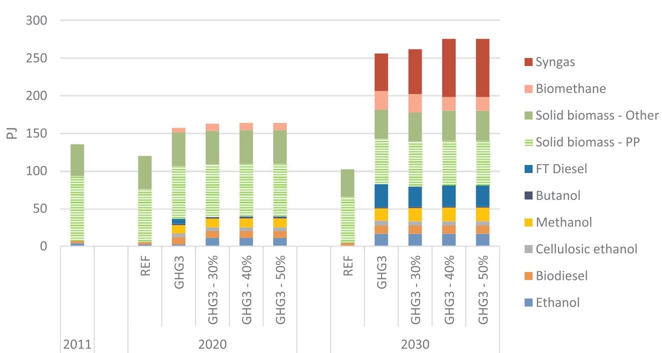

Fig. 10. Bioenergy consumption by type with decreasing cost of forest residues in Quebec.

national energy systems under different climate and energy policies. In their analysis of the evolution of the Swedish energy system under a GHG emission reduction target of 80% in 2050, Börjesson et al. [12] observed an annual growth rate for road transport biofuels of 6% from 2010 to 2050 with biofuels accounting for 23% of road transport final energy in 2030. In comparison, we showed that in 2030, biofuels account for 7–13% of passenger road transportation in Quebec, and 2–11% of freight transportation, depending on GHG emission reduction scenarios, which are less stringent than for the Swedish case analyzed. Zhao et al. [13] found that liquid biofuels would account for 6–16% of the total transport energy demand in China by 2050. They also found that in the short-term, this share is highly dependent on feedstock cost, as we also concluded in our study. Besides, Dodder et al. [14] showed that biofuel penetration in the United States mostly depends on the availability of cellulosic feedstock, and on oil and natural gas prices.

In their analysis on the penetration of bioenergy in stationary applications, Panos and Kannan [16] found that domestic biomass can contribute to 5–7% of electricity and 14–21% of heat production by 2050 depending on natural gas prices and climate policy intensity. Similarly, König [17] showed that heat generation as well as combined heat and power (CHP) production from solid biomass are the most cost effective ways to contribute to the emission reduction targets. We found that bioenergy is not significantly used to produce electricity and heat in Quebec, mainly because of the low-cost hydropower potential of the province.

Finally, Hugues et al. [15] found highly variable marginal costs of abatement in their study on biofuel markets in France. These were going from 200 €/tCO_2eq to 6000 €/tCO_2eq for different assumptions regarding mitigation level constraints and learning curves. The advanced biofuels share ranges from 20% (reference scenario) to 56% (high mitigation level and important learning cost reduction scenario). As a comparison, in our study, we found marginal costs of abatement of 258 $/t$CO_2$eq to 581 $/t$CO_2$eq depending on GHG emission reduction scenarios.

5.3. Comparison with energy policy targets

Besides adopting a GHG emission reduction target for 2030 (37.5% reduction below 1990 levels), the province of Quebec has adopted several energy targets for 2030 (from 2013 levels) in its 2030 Energy Policy [43], such as: reduce the amount of petroleum products consumed by 40%, increase overall renewable energy output by 25%, and increase bioenergy production by 50%. It is important to note that this energy policy is expected to contribute to meeting the provincial GHG emission reduction target, but additional measures (e.g., reduction from non-energy uses) are also envisioned. By contrast, NATEM computes the optimal configuration of the energy sector consistent with abating energy related GHG emissions by the desired amount.

Concerning the reduction of petroleum products consumed, NATEM computes a 39% reduction in the GHG3 scenario, and a 40% reduction in GHG4 (by 2030 from 2013 levels), thus about the same as the proposed energy target. In terms of overall renewable energy output, NATEM calculates a 64% increase in GHG3, and a 67% increase in GHG4. Finally, NATEM computes a 99% increase in bioenergy production in the GHG3 scenario, and a 119% increase in GHG4. Our study envisions thus a much larger penetration of bioenergy (about twice as much) than the one proposed in the 2030 Energy Policy by the government of Quebec.

6. Conclusion

In this article, we have presented a study that analyzes the potential penetration of bioenergy in Quebec by 2030 under different GHG emission reduction scenarios. We have used NATEM, a prospective detailed, multi-regional, optimization model of the Canadian energy sector based on the TIMES framework. In order to achieve the desired GHG emission abatement levels, the needed energy transition involves in particular: i) an endogenous reduction in energy service demands; ii) energy efficiency improvements through technological substitutions; iii) greater penetration of electricity in all sectors to the detriment of oil

and natural gas (from 12% in the REF scenario to 6% in the GHG4 scenario); and iv) a larger role for bioenergy in 2030 (from 6% in the REF scenario to 18% in the GHG4 scenario). Concerning bioenergy, we also find that the total amount of feedstock used for bioenergy production increases in 2030, from 105 PJ in the REF scenario to 422 PJ in the GHG4 scenario, and that remaining potential exist at higher cost. However, the analysis would benefit from exploring the effects of the most uncertain assumptions on the optimal solutions, such as the future costs of second-generation biofuel conversion processes and the integration of more advanced options not commercially available today (biofuel production from algae, etc.).

Rising demand for biomass feedstock might lead to an intensification of agriculture and forest management, as well as increased pressure on land. This could result in increased non-energy-related GHG emissions [44] that cannot be tackled by a prospective energy system model like TIMES. Studies typically consider impacts of biofuel policies on energy systems and other sectors separately. For effective policy-making, it could be interesting to understand the full implications of biofuels on other markets. This could be done in the future by combining NATEM with other techno-economic models, following for instance Dodder et al. [14] who combined a TIMES model with an agriculture model. Moreover, combining NATEM with a general equilibrium model could allow accounting for socio-economic impacts in addition to GHG emissions [46].

In this study, we followed a biogenic carbon neutrality principle, assuming that an equivalent amount of CO_2 is sequestered from the atmosphere by growing biomass. However, this assumption is increasingly criticized, with several studies showing that this could lead to accounting errors and biased decision-making [see, e.g., 45]. Moreover, the changes observed in the energy system could lead to non-climate environmental impacts.

To address these issues, our future research will use a consequential life-cycle assessment (LCA) to evaluate potential environmental impacts associated with the deployment of next-generation biofuel pathways in Quebec and Canada. In this paper, NATEM was used to identify how the Quebec energy system reacts to the introduction of new biofuels under different policy contexts. For the LCA, the differences in the energy system configuration between a reference and policy scenarios will be modeled using an LCA software, results of NATEM, and generic data from a life cycle inventory database. The use of economic models to perform consequential LCAs is an emerging topic and require the definition of a structure to share data between both types of models.

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